



Parallel universe, dark matter and invisible Higgs decays



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ABSTRACT

The existence of the dark matter with amount about five times the ordinary matter is now well established experimentally. There are now many candidates for this dark matter. However, dark matter could be just like the ordinary matter in a parallel universe. If both universes are described by a non-abelian gauge symmetries, then there will be no kinetic mixing between the ordinary photon and the dark photon, and the dark proton, dark electron and the corresponding dark nuclei, belonging to the parallel universe, will be stable. If the strong coupling constant, $(\alpha_s)_{\text{dark}}$ in the parallel universe is five times that of α_s , then the dark proton will be about five time heavier, explaining why the dark matter is five times the ordinary matter. However, the two sectors will still interact via the Higgs boson of the two sectors. This will lead to the existence of a second light Higgs boson, just like the Standard Model Higgs boson. This gives rise to the invisible decay modes of the Higgs boson which can be tested at the LHC, and the proposed ILC.

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1. Introduction

Symmetry seems to play an important role in the classification and interactions of the elementary particles. The Standard Model (SM) based on the gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$ has been extremely successful in describing all experimental results so far to a precision less than one percent. The final ingredient of the SM, namely the Higgs boson, has finally been observed at the LHC [1]. However, SM is unable to explain why the charges of the elementary particle are quantized because of the presence of $U(1)_Y$. This was remedied by enlarging the $SU(3)_C$ symmetry to $SU(4)_C$ with the lepton number as the fourth color (or grand unifying all three interaction in SM in $SU(5)$ [2] or $SO(10)$ [3]).

SM also has no candidate for the dark matter whose existence is now well established experimentally [4]. Many extensions of the SM models, such as models with weakly interacting massive particles (WIMP) can explain the dark matter [4]. The most popular examples are the lightest stable particles in supersymmetry [4], or the lightest Kaluza–Klein particle in extra dimensions [5]. Of course, axion [6] is also a good candidate for dark matter. Several experiments are ongoing to detect signals of dark matter in the laboratory. However, it is possible that the dark matter is just the analogue of ordinary matter belonging to a parallel universe. Such a parallel universe naturally appears in the superstring the-

ory with the $E_8 \times E'_8$ gauge symmetry before compactification [7]. Parallel universe in which the gauge symmetry is just the replication of our ordinary universe, i.e. the gauge symmetry in the parallel universe being $SU(3)' \times SU(2)' \times U(1)'$ has also been considered [8]. If the particles analogous to the proton and neutron in the parallel universe is about five times heavier than the proton and neutron of our universe, then that will naturally explain why the dark matter of the universe is about five times the ordinary matter. This can be easily arranged by assuming strong coupling constant square/ 4π , α'_s is about five times larger than the QCD α_s . Thus, in this work, we assume that the two universe where the electroweak sector is exactly symmetric, whereas the corresponding couplings in the strong sector are different, explaining why the dark matter is larger than the ordinary matter. Also, we assume that both universes are described by non-abelian gauge symmetry so that the kinetic mixing between the photon (γ) and the parallel photon (γ') is forbidden. We also assume that post-inflationary reheating in the two worlds are different, and the parallel universe is colder than our universe [9]. This makes it possible to maintain the successful prediction of the big bang nucleosynthesis, though the number of degrees of freedom is increased from the usual SM of 10.75 at the time of nucleosynthesis due the extra light degrees of freedom (due to the γ' , e' and three ν 's).

In this work, we explore the LHC implications of this scenario due to the mixing among the Higgs bosons in the two electroweak sectors. Such a mixing, which is allowed by the gauge symmetry, will mix the lightest Higgs bosons of our universe (h_1) and the lightest Higgs boson of the parallel universe (h_2), which we

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will call the dark Higgs. One of the corresponding mass eigenstates, h_{SM} we identify with the observed Higgs boson with mass of 125 GeV. The other mass eigenstate, which we denote by h_{DS} , the dark Higgs, will also have a mass in the electroweak scale. Due to the mixing effects, both Higgs will decay to the kinematically allowed modes in our universe and as well as to the modes of the dark universe. One particularly interesting scenario is when the two Higgs bosons are very close in mass, say within 4 GeV so that the LHC cannot resolve it [10]. However, this scenario will lead to the invisible decay modes [11]. The existence of such invisible decay modes can be established at the LHC when sufficient data accumulates. (The current upper limit on the invisible decay branching ratio of the observed Higgs at the LHC is 0.65.) At the proposed future International Linear Collider (ILC) [12], the existence of such invisible modes can be easily established, and the model can be tested in much more detail.

2. Model and the formalism

The gauge symmetry we propose for our work is $SU(4)_C \times SU(2)_L \times SU(2)_R$ for our universe, and $SU(4)'_C \times SU(2)'_L \times SU(2)'_R$ for the parallel universe. Note that we choose this non-abelian symmetry not only to explain charge quantization (as in Pati–Salam model [13]), but also to avoid the kinetic mixing of γ and γ' as would be allowed in the Standard Model. All the elementary particles belong to the representations of this symmetry group and their interactions are governed by this symmetry. The 21 gauge bosons belong to the adjoint representations (15, 1, 1), (1, 3, 1), (1, 1, 3). (15, 1, 1) contains the 8 usual colored gluons, 6 lepto-quark gauge bosons (X, \bar{X}), and one ($B - L$) gauge boson [14]. (1, 3, 1) contains the 3 left handed weak gauge bosons, while (1, 1, 3) contains the 3 right handed weak gauge bosons. The parallel universe contains the corresponding parallel gauge bosons. However, so far as the gauge interactions are concerned, we do not assume that the coupling for $SU(4)$ and $SU(4)'$ interactions are the same, but strong coupling in the parallel universe is larger in order to account for the p' (proton of the parallel universe) mass to be about five times larger than the proton. For the electroweak sector, we assume the exact symmetry between our universe and the parallel universe.

The fermions belong to the fundamental representations (4, 2, 1) + (4, 1, 2). The 4 represent three color of quarks and the lepton number as the 4th color, (2, 1) and (1, 2) represent the left and right handed doublets. The forty eight Weyl fermions belonging to three generations may be represented by the matrix

$$\begin{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix}_1 & \begin{pmatrix} u \\ d \end{pmatrix}_2 & \begin{pmatrix} u \\ d \end{pmatrix}_3 & \begin{pmatrix} \nu_e \\ e \end{pmatrix}_4 \\ \begin{pmatrix} c \\ s \end{pmatrix}_1 & \begin{pmatrix} c \\ s \end{pmatrix}_2 & \begin{pmatrix} c \\ s \end{pmatrix}_3 & \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_4 \\ \begin{pmatrix} t \\ b \end{pmatrix}_1 & \begin{pmatrix} t \\ b \end{pmatrix}_2 & \begin{pmatrix} t \\ b \end{pmatrix}_3 & \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_4 \end{pmatrix}_{L,R} \quad (1)$$

We have similar fermion representations for the parallel universe, denoted by primes.

The model has 3 gauge coupling constants: g_4 for $SU(4)$ color which we will identify with the strong coupling constant of our universe, g'_4 for $SU(4)'$ color of the parallel universe, and g for $SU(2)_L$ and $SU(2)_R$, and corresponding electroweak couplings for the parallel universe ($g_L = g_R = g'_L = g'_R = g$) (we assume that the

gauge couplings of the electroweak sectors of the two universe are the same).

2.1. Symmetry breaking

$SU(4)$ color symmetry is spontaneously broken to $SU(3)_C \times U(1)_{B-L}$ in the usual Pati–Salam way using the Higgs fields (15, 1, 1) at a scale V_C . The most stringent lower limit of 2300 TeV on the scale of this symmetry breaking in the visible sector comes from the upper limit of the rare decay mode $K_L \rightarrow \mu e$ [15]. Dark sector particles are invisible. Therefore, there is no direct or indirect search limit on the symmetry breaking scale in the dark sector. However, we have assumed that the gauge symmetry and symmetry breaking structure in the parallel universe is just the replication of our ordinary universe. Therefore, we have assumed that the lower limit for the symmetry breaking scale in the visible sector is also valid for the dark sector. $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ can be broken to the SM using the Higgs representations (1, 2, 1) and (1, 1, 2) at a scale V_{LR} . Alternatively, one can use the Higgs multiplets (1, 3, 1) and (1, 1, 3) if we want to generate the light neutrino masses at the observed scale. Finally the remaining symmetry is broken to the $U(1)_{EM}$ using the Higgs bi-doublet (1, 2, 2) as in the left–right model. The (15, 2, 2) Higgs multiplet could also be added to eliminate unwanted mass relations among the charged fermions. Similar Higgs representations are used to break the symmetry in the parallel universe to $U'(1)_{EM}$. A study of the Higgs potential shows that there exists a parameter space where only one neutral Higgs in the bi-doublet remains light, and becomes very similar to the SM Higgs in our universe [16]. The Higgs fields arising from the (1, 2, 1) and (1, 1, 2) representations will have masses in the left–right symmetry breaking scale, V_{LR} [16] for which the current limit is $\simeq 3$ TeV, and thus very heavy compared to the EW scale, $\simeq 250$ GeV. The Higgs fields arising from (15, 1, 1) is much heavier with masses in the 1st stage of the symmetry breaking scale which is $\simeq 2300$ TeV as mentioned above. Similar is true in the parallel universe. We note that this non-supersymmetric model does have fine tuning to preserve the two light Higgs bosons. This fine tuning corresponds to cancellation between the terms in left–right symmetry breaking scale \sim few TeV. When the Higgs field (15, 2, 2) is included, the fine tuning is between the terms in the \sim few thousand TeV scale. We have assumed a discrete symmetry between visible and dark Higgses in the scalar potential: $H_{Visible} \leftrightarrow H_{Dark}$. This symmetry of the Higgs fields in the EW sector between our universe and the parallel universe will make the two electroweak VEV's the same. Thus the mixing terms between the two bi-doublets (one in our universe and one in the parallel universe) then leads to mixing between the two remaining SM like Higgs fields. The resulting mass terms for the remaining two light Higgs fields can be written as $m_{VS}^2 h_1^2 + m_{DS}^2 h_2^2 + 2\lambda v_{VS} v_{DS} h_1 h_2$ (where v_{VS} and v_{DS} are the electroweak symmetric breaking scales in the visible sector and dark sector respectively) from which the two mass eigenstates and the mixing can be calculated. The implications for this is when the two light Higgses are very close in mass (within about 4 GeV, which LHC cannot resolve) leads to the invisible decay of the observed Higgs boson. Below we discuss the phenomenological implications for this scenario at the LHC, and briefly at the proposed ILC [12].

3. Phenomenological implications

In the framework of this model, interaction between fermions and/or gauge bosons of dark sector and visible sector (the SM particles) are forbidden by the gauge symmetry. However, quartic Higgs interactions of the form $\lambda (H_{VS}^\dagger H_{VS})(H_{DS}^\dagger H_{DS})$ (where H_{VS} and H_{DS} symbols denote the Higgs fields in the visible sector and

dark sector respectively) are allowed by the gauge symmetry and give rise to mixing between the Higgses of dark and visible sector. The mixing between the lightest Higgses of dark sector and visible sector gives rise to interesting phenomenological implications at the collider experiments. In this section, we will discuss the phenomenological implications of the lightest dark and visible neutral Higgs mixing (h_1 and h_2). As discussed in the previous section, the bi-linear terms involving the lightest visible sector (denoted by h_1) and dark sector (denoted by h_2) Higgses in the scalar potential are given by

$$\mathcal{L}_{\text{Scalar}} \supset m_{VS}^2 h_1^2 + m_{DS}^2 h_2^2 + 2\lambda v_{VS} v_{DS} h_1 h_2 \quad (2)$$

where v_{VS} and v_{DS} are the electroweak symmetric breaking scales in the visible sector and dark sector respectively. In our analysis, we have assumed a discrete symmetry between visible sector scalars and corresponding dark sector scalars which makes both v_{VS} and v_{DS} equal to the SM electroweak symmetry breaking scale $v_{SM} \sim 250$ GeV. m_{VS} , m_{DS} and λ are the free parameters in the theory and the masses ($m_{h_1^{(p)}}$ and $m_{h_2^{(p)}}$) and mixing between physical light Higgs states (denoted by $h_1^{(p)}$ and $h_2^{(p)}$) are determined by these parameters:

$$\begin{aligned} h_1^{(p)} &= \cos \theta h_1 + \sin \theta h_2, \\ h_2^{(p)} &= -\sin \theta h_1 + \cos \theta h_2, \end{aligned} \quad (3)$$

where the masses and the mixing angle of these physical states are given by

$$\begin{aligned} m_{h_1^{(p)}, h_2^{(p)}}^2 &= \frac{1}{2} \left[(m_{VS}^2 + m_{DS}^2) \mp \sqrt{(m_{VS}^2 - m_{DS}^2)^2 + 4\lambda^2 v_{VS}^2 v_{DS}^2} \right] \\ \tan 2\theta &= \frac{2\lambda v_{VS} v_{DS}}{m_{DS}^2 - m_{VS}^2}. \end{aligned} \quad (4)$$

It is important to note that this discrete symmetry in the scalar potential also ensures the equality of m_{VS} and m_{DS} which gives rise to the maximal mixing between the visible and dark sector Higgses. As a result, in our analysis, we have assumed that this discrete symmetry of the scalar potential is softly broken by the dimension-2 terms in the scalar potential which allows m_{VS} and m_{DS} to be different.

In the framework of this model, we have two light physical neutral Higgs ($h_1^{(p)}$ and $h_2^{(p)}$) states. Out of these two Higgs states, we define the SM like Higgs h_{SM} is the state which is dominantly h_1 -like, i.e., if $\cos \theta > \sin \theta$ then $h_{SM} = h_1^{(p)}$ and vice versa. The other Higgs is denoted as dark Higgs (h_{DS}). Since ATLAS and CMS collaborations have already detected an SM like Higgs boson with mass about 125 GeV, we only studied the scenario where the mass of h_{SM} is between 123 and 127 GeV. Before going into the details of collider implication of visible sector and dark sector Higgs mixing, it is important to understand the correlation between the mixing and mass of the dark Higgs ($m_{h_{DS}}$). To understand the correlation, for few fixed values of λ , we have scanned the $m_{VS} - m_{DS}$ parameter space. We have only considered the points which gives rise to an h_{SM} in the mass range between 123 and 127 GeV. For these points, the resulting dark Higgs masses ($m_{h_{DS}}$) and mixing (θ) are plotted in Fig. 1. The scatter plot in Fig. 1 shows that large mixing in the visible and dark sector is possible only when the dark Higgs mass is near 125 GeV i.e., near the mass of SM like Higgs boson. It is important to note that the LHC is a proton–proton collider, i.e., LHC collides the visible sector particles only. Therefore, the production cross-section of dark Higgs at the LHC is proportional to the

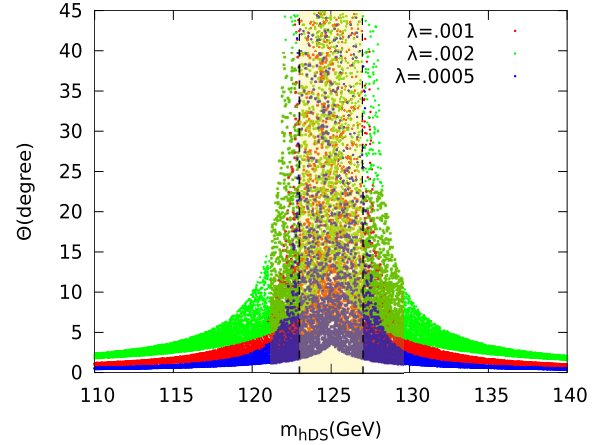


Fig. 1. Scatter plot of dark Higgs mass vs. mixing angle for different values of λ . The SM-like Higgs mass is kept fixed in the range between 123 and 127 GeV denoted by the shaded region in the plot.

square of the visible sector Higgs component in h_{DS} . Therefore, in order to detect the signature of dark Higgs at the collider experiments, we must have significant mixing between the visible and dark sector Higgses. And Fig. 1 shows that significant mixing arises only when dark Higgs and SM like Higgs are nearly degenerate in mass. Therefore, in this article, we studied the phenomenology of two nearly degenerate Higgs bosons with mass about 125 GeV.

3.1. Interactions and decays of light Higgses

In the present model, two light Higgs physical states ($h_1^{(p)}$ and $h_2^{(p)}$) result from the mixing of visible sector and dark sector light Higgs weak eigenstate h_1 and h_2 respectively. Visible sector light Higgs weak eigenstates, h_1 interacts only with the visible sector fermions (f) via Yukawa interactions and gauge bosons (V) via gauge interactions. Whereas the dark sector light Higgs weak eigenstate interacts only with the dark fermions f_D and dark gauge bosons V_D . However, as a result of mixing, the physical light Higgses interact with both the visible particles and dark particles and thus, they can be produced at the Large Hadron Collider (LHC) experiment. The coupling of the physical states $h_1^{(p)}$ and $h_2^{(p)}$ with the visible as well as dark fermions and gauge bosons can be written as a product of corresponding SM coupling and sine or cosine of the mixing angle. As a result the production cross sections of $h_1^{(p)}$ and $h_2^{(p)}$ and decay widths into visible as well as dark particles can be computed in terms of the SM Higgs production cross-sections/decay widths and the mixing angle. For example, total $h_1^{(p)}$ production cross section at the LHC is given by $\sigma_{SM} \cos^2 \theta$, where σ_{SM} is the production cross-section of the SM Higgs with equal mass. Similarly, the decay widths of $h_1^{(p)}$ ($h_2^{(p)}$) into visible and dark sector fermions are given by $\Gamma_{SM}^{H \rightarrow f\bar{f}} \cos^2 \theta$ ($\Gamma_{SM}^{H \rightarrow f\bar{f}} \sin^2 \theta$) and $\Gamma_{SM}^{H \rightarrow f\bar{f}} \sin^2 \theta$ ($\Gamma_{SM}^{H \rightarrow f\bar{f}} \sin^2 \theta$) respectively, where $\Gamma_{SM}^{H \rightarrow f\bar{f}}$ is the decay width of the SM Higgs into fermions. It is important to note that since the QCD coupling in the dark sector is about 5 times larger than the QCD coupling in the visible sector, the Higgs coupling with dark gluon in this model is enhanced by a factor about 5.

In this analysis we are considering both the Higgs states in the mass range between 123 and 127 GeV. Here we present the expressions for $\mu = \sigma/\sigma_{SM}$ and total $\sigma \times BR_{invisible}$ for the present model,

Table 1
Standard Model production cross section (pb) in different channels for $E_{CM} = 8$ TeV.

Mass of Higgs (GeV)	σ_{ggf}	σ_{ttH}	σ_{VBF}	σ_{Vh}
123	20.15	1.608	1.15	0.1366
124	19.83	1.595	1.12	0.1334
125	19.52	1.578	1.09	0.1302
126	19.22	1.568	1.06	0.1271
127	18.92	1.552	1.03	0.1241

$$\mu = \frac{(\sigma_{h1} \cos^4 \theta BR_{h1} / (1 + 24BR_{h1}^{gg} \sin^2 \theta))}{\sigma_{SM} * BR} + \frac{(\sigma_{h2} \sin^4 \theta BR_{h2} / (1 + 24BR_{h2}^{gg} \cos^2 \theta))}{\sigma_{SM} * BR}$$

$$\sigma \times BR_{inv} = \frac{\sigma_{h1} \cos^2 \theta \sin^2 \theta (BR_{h1}^{inv} + 25BR_{h1}^{gg})}{1 + 24BR_{h1}^{gg} \sin^2 \theta} + \frac{\sigma_{h2} \cos^2 \theta \sin^2 \theta (BR_{h2}^{inv} + 25BR_{h2}^{gg})}{1 + 24BR_{h2}^{gg} \cos^2 \theta} \quad (5)$$

where σ_{h1} corresponds to Standard Model Higgs production cross-section at mass of $h_1^{(p)}$ and σ_{h2} corresponds to Standard Model production cross-section at mass of $h_2^{(p)}$ (see Table 1) and BR_{h1} , BR_{h2} and BR corresponds to branching ratios of the SM Higgs boson at the mass of $h_1^{(p)}$, $h_2^{(p)}$ and 125 GeV respectively (see Table 2) in the particular channel¹ under consideration.

3.2. Data used in collider analysis

In this section, we discuss the collider phenomenology of invisible Higgs decays. Before going into the details of the collider prediction, we first need to study the constraints on the parameter space coming from the present Standard Model predictions and experimental data. The Higgs mass eigenstates of h_{SM} and h_{DS} will be produced in colliders through the top loop as top quark has Standard Model couplings to the h_{SM} mass eigenstate. The Higgs, which comprises of both h_1 and h_2 eigenstates, will then decay in both the Standard Model decay modes along with dark sector decay modes. We will perceive these dark sector decay modes as enhancement in the invisible branching fraction of the Higgs.

We first discuss the different constraints on the mixing angle θ between the two eigenstates coming from experimental data of $H \rightarrow WW \rightarrow l\nu l\nu$ and $H \rightarrow \gamma\gamma$ channels. Along with these experimental data in Higgs decays in different modes, we have also taken into account constraints on the mixing angle parameter space coming from the ATLAS search for the invisible decays of a 125 GeV Higgs boson produced in association with a Z boson [11].

The Standard Model production cross-sections in different channels (such as gluon–gluon fusion, ttH , vector boson fusion and vector boson (both W boson and Z boson) in association with a

¹ In our analysis, we only consider $H \rightarrow WW \rightarrow l\nu l\nu$ and $H \rightarrow \gamma\gamma$ channels.

Table 2
Standard Model decay branching ratio in different channels.

Mass of Higgs (GeV)	$BR(H \rightarrow WW)$	$BR(H \rightarrow ZZ)$	$BR(H \rightarrow \gamma\gamma)$	$BR(H \rightarrow gg)$	$BR(H \rightarrow ff)$
123	0.183	2.18×10^{-2}	2.27×10^{-3}	8.71×10^{-2}	0.687
124	0.199	2.41×10^{-2}	2.27×10^{-3}	8.65×10^{-2}	0.687
125	0.215	2.64×10^{-2}	2.28×10^{-3}	8.57×10^{-2}	0.670
126	0.231	2.89×10^{-2}	2.28×10^{-3}	8.48×10^{-2}	0.651
127	0.248	3.15×10^{-2}	2.27×10^{-3}	8.37×10^{-2}	0.633

Table 3
Experimental values of best fit signal strength $\mu = \sigma/\sigma_{SM}$ at $E_{CM} = 8$ TeV.

Channels for Higgs decay	μ value by ATLAS	μ value by CMS
$H \rightarrow WW \rightarrow l\nu l\nu$	1.01 ± 0.31	0.76 ± 0.21
$H \rightarrow \gamma\gamma$	$1.65 \pm 0.24(stat)^{+0.25}_{-0.18}(syst)$	0.78 ± 0.27

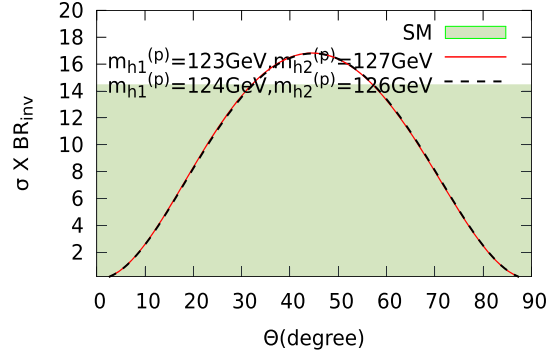


Fig. 2. Decay rate in invisible channels in the present model as a function of mixing angle θ . The shaded regions correspond to SM allowed values for $\sigma \times BR_{inv}$.

Higgs boson) at $E_{CM} = 8$ TeV and decay branching ratios in different channels (such as $H \rightarrow WW$, $H \rightarrow ZZ$, $H \rightarrow \gamma\gamma$, $H \rightarrow gg$, $H \rightarrow ff$) has been given by ATLAS collaboration in Ref. [17]. We have used these cross-sections and branching ratios in different channels in our analysis. The relevant cross-sections and branching ratios used for our analysis are presented in Table 1 and Table 2 respectively. We have taken the mass range between 123 and 127 GeV which is the interesting parameter space for our analysis.

In Table 3 we present the results of the different experimental searches in the $H \rightarrow WW \rightarrow l\nu l\nu$ channel by ATLAS collaborations [18] and CMS collaboration [19] and in $H \rightarrow \gamma\gamma$ channel by ATLAS collaboration [20] and CMS collaboration [21].

3.3. Bounds on mixing angle

In this section we use the data that we presented in the previous section to constrain the mixing angle parameter space. In Fig. 2, we present the total invisible decay rate, in the framework of the present model, as a function of the mixing angle θ for $m_{h1}^{(p)} = 123$ GeV and $m_{h2}^{(p)} = 127$ GeV ($m_{h1}^{(p)} = 124$ GeV and $m_{h2}^{(p)} = 126$ GeV). ATLAS collaboration has searched for the invisible decay of Higgs boson in ZH production channel at $E_{CM} = 8$ TeV. In absence of any significant deviation of data from the Standard Model background prediction, ATLAS collaboration has set an upper limit of 65% on the invisible decay branching of an SM Higgs boson of mass 125 GeV [11]. Assuming $\sigma_{total} = 22.32$ pb Higgs cross-section at 125 GeV (see Table 1), 65% upper limit on invisible decay branching ratio corresponds to 14.5 pb upper limit on the invisible Higgs decay rate. This limit is shown in the shaded green region in Fig. 2. It can be seen from the plot that the present

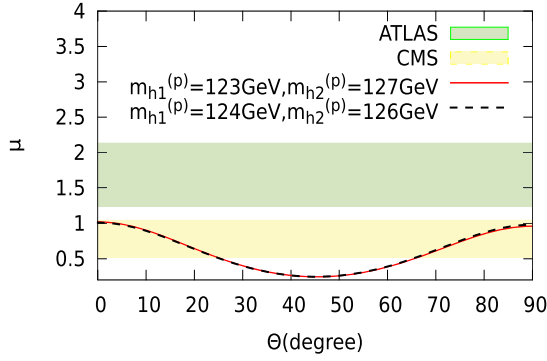


Fig. 3. Higgs decaying into diphoton rate in the present model as a function of mixing angle θ . The shaded regions again correspond to ATLAS and CMS allowed $\mu = \sigma/\sigma_{SM}$ values. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

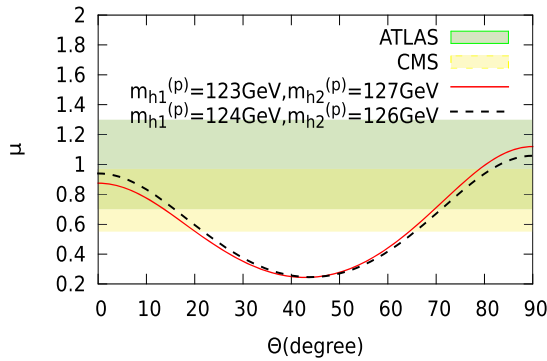


Fig. 4. $H \rightarrow WW \rightarrow l\nu l\nu$ rate in the present model as a function of mixing angle θ . The shaded regions correspond to ATLAS and CMS allowed $\mu = \sigma/\sigma_{SM}$ values. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

model is consistent with ATLAS experimental data for $\theta < 33^\circ$ and $\theta > 58^\circ$ in the parameter space region.

In Fig. 3 we have presented a plot of $\mu = \sigma/\sigma_{SM}$ in the $H \rightarrow \gamma\gamma$ channel as a function of the mixing angle θ . The plot shows prediction in the present model for $m_{h1}^{(p)} = 123$ GeV and $m_{h2}^{(p)} = 127$ GeV ($m_{h1}^{(p)} = 124$ GeV and $m_{h2}^{(p)} = 126$ GeV) mass values. The yellow shaded region corresponds to allowed region by CMS collaboration and green shaded region is allowed region for ATLAS collaboration in this channel. It can be seen from the plot that CMS allowed region is consistent for all θ 's for the present model, but the present model is not consistent with ATLAS allowed region for any values of θ . We point out that $H \rightarrow \gamma\gamma$ data for ATLAS, is well above the SM expectation. If the present model is realized by nature, with the accumulation of more data with higher luminosities at the Large Hadron Collider (LHC) the $H \rightarrow \gamma\gamma$ branching ratio measured by ATLAS experiment should come down significantly from the present experimental value of $1.65 \pm 0.24(\text{stat})^{+0.25}_{-0.18}(\text{syst})$. Our model is consistent with the lower μ value of 0.78 ± 0.27 for $H \rightarrow \gamma\gamma$ as measured by the CMS experiment for the whole parameter of the parameter space.

In Fig. 4 we present a plot of $\mu = \sigma/\sigma_{SM}$ in the $H \rightarrow WW \rightarrow l\nu l\nu$ channel with mixing angle θ . Two curves for $m_{h1}^{(p)} = 123$ GeV and $m_{h2}^{(p)} = 127$ GeV ($m_{h1}^{(p)} = 124$ GeV and $m_{h2}^{(p)} = 126$ GeV) present the prediction for the present model. The yellow shaded region corresponds to allowed region by CMS collaboration and green shaded region is for allowed region by ATLAS collaboration in this channel. It can be seen from the plot that ATLAS allowed region is consistent with the present model for $\theta < 13(16)^\circ$ and

$\theta > 70(71)^\circ$ region in the parameter space. It can also be seen that the present model is also consistent with CMS allowed region for $\theta < 20(23)^\circ$ and $\theta > 65(66)^\circ$ parameter space. It is interesting to note that the prediction curves for the present model with mass values of $m_{h1}^{(p)} = 123$ GeV and $m_{h2}^{(p)} = 127$ GeV ($m_{h1}^{(p)} = 124$ GeV and $m_{h2}^{(p)} = 126$ GeV) are not symmetric. It can be understood by taking into the fact that in low θ region $m_{h1}^{(p)}$ is SM like. As $m_{h1}^{(p)}$ is lower than $m_{h2}^{(p)}$ for both curves, the cross-section \times branching ratio is smaller in lower θ region. Whereas for high θ region $m_{h2}^{(p)}$ is SM like and as it is heavier than $m_{h1}^{(p)}$ for both curves the cross section \times branching ratio is higher in this region, which makes the curves non-symmetric.

The present analysis in the $H \rightarrow WW \rightarrow l\nu l\nu$ channel gives the most stringent constraint of $\theta < 13(16)^\circ$ and $\theta > 70(71)^\circ$ on the parameter space for the mixing angle θ taking into account all the constraints coming from analysis in $\sigma \times BR_{\text{invisible}}$, $H \rightarrow \gamma\gamma$ and $H \rightarrow WW \rightarrow l\nu l\nu$ channels. From this analysis in different channels it is certain that there is still plenty of parameter space available for the present model taking into account all the known experimental constraints at the LHC.

We would also like to comment that in a linear collider like the proposed International Linear Collider (ILC) this analysis can be done without any ambiguity about the resolution of the two Higgs in the close range of 4 GeV. In an e^+e^- collider the Higgs will be produced in association with a Z boson and from the mass recoil of the Z boson the peak resolution of the Higgs boson can be measured in the limit of 40 MeV [12]. So from linear colliders we will be able to tell for sure if there are two Higgs bosons in the comparable mass range between 123 and 127 GeV, which is not possible in this precision from hadron collider like LHC.

4. Summary and conclusions

Motivated by the fact that the dark matter is about five times the ordinary matter, we have proposed that the dark matter can just be like the ordinary matter in a parallel universe with the corresponding strong coupling constant, α'_s about five times the strong coupling, α_s of our universe. The parallel universe needs to be much colder than our universe to keep the successful prediction for the big bang nucleosynthesis. We have used the non-abelian Pati–Salam gauge symmetry for both universe to have the charge quantization, as well as, to avoid any kinetic mixing between the photon of our universe and the parallel universe. However, the two universes will be connected via the electroweak Higgs bosons of the two universes. If the electroweak sector of the two universes are symmetric, the lightest Higgs bosons of the two universes will mix. In particular, if these two Higgses mix significantly, and their masses are close (say within 4 GeV), LHC will not be able to resolve if it is observing one Higgs or two Higgses. However, each Higgs will decay to the particles of our universe as well as to the corresponding particles of the parallel universe. This leads to the invisible decays of the observed Higgs boson (or bosons). We have used all the available experimental data at the LHC to set constraint on this mixing angle, and find that it can be as large as 16° . If the mixing angle is not very small, LHC will be able to infer the existence of such invisible decays when sufficient data accumulates. (The current limit on the invisible branching ratio from the LHC data is $< 65\%$.) We also find that the cross section times the branching ratio for Higgs to $\gamma\gamma$ channel is fully consistent with our model as measured by the CMS collaboration, but not by the ATLAS collaboration. The results by the ATLAS collaboration for this channel has to come down if our model is realized by nature. Our proposal of two Higgses around 125 GeV, and significant invisible decay fraction can easily be tested in the proposed

ILC where peak resolution of the Higgs boson can be measured to about 40 MeV.

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